



Multi-messenger astronomy

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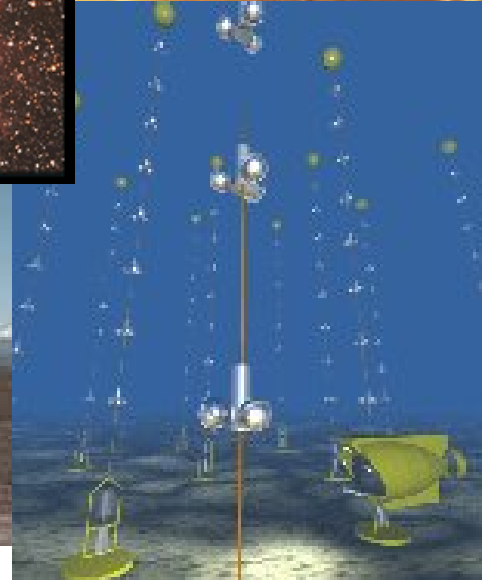
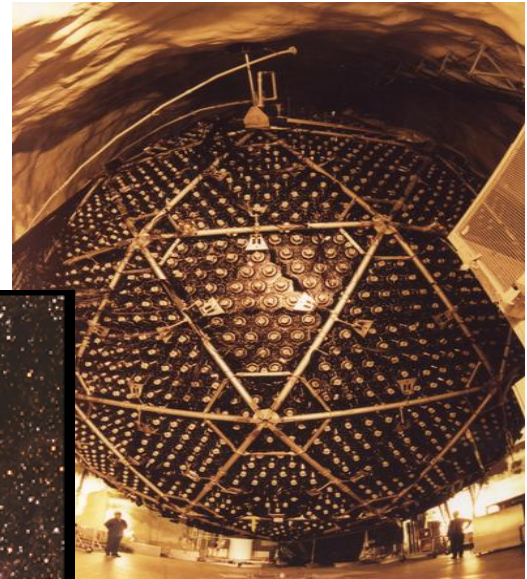
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Multi-messenger Astronomy

Michel DAVIER

LAL-Orsay



M. Davier Neutrino 2004
Paris 11-16 June 2004

General Remarks

- A vast subject and a very active field
- Multi-messengers:
 - photons (radio, IR, visible, X- and γ -rays)
 - protons and nuclei
 - neutrinos
 - a new comer: gravitational waves
- The Universe looks very different with different probes
- However: important to observe the same events
- Very selective review (focus on interplay)

Outline

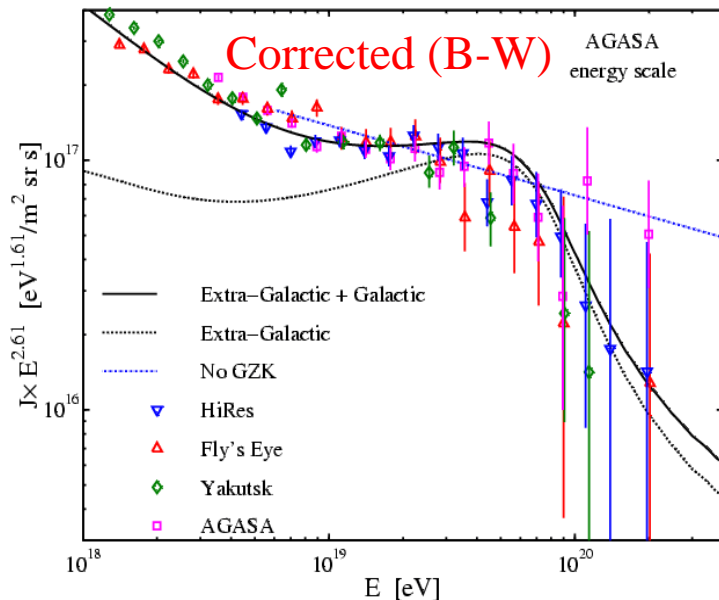
- UHE Cosmic Rays
- γ -ray Bursts
- Investigating Dark Matter with γ -rays
- GW signals : the next galactic SN
(a generic case)

UHE Cosmic Rays

- Energy spectrum extends to $\sim 10^{20}$ eV
- Shoulder $\sim 5 \cdot 10^{19}$ eV
- Big questions:
 - Where are the accelerators ? How do they work?
 - Is the GZK cutoff seen ?

AGASA, Fly's Eye,
Yakutsk, HiRes

Problem: energy scale



proton interactions with CMB photons
energy loss distance much reduced

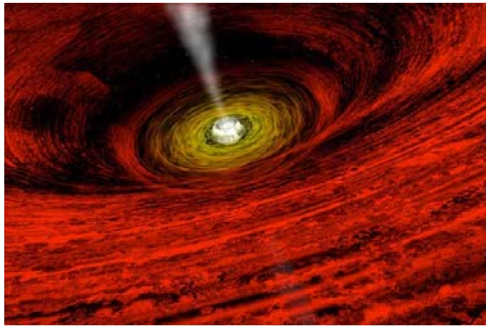
10 Mpc	10^{20} eV
1 Gpc	$0.5 \cdot 10^{20}$ eV

evidence for GZK? (Bahcall-Waxman 03)

Auger expt should settle this point
expect ~ 30 evts/yr above 10^{20} eV

GRB : Facts and Interpretation

- Short variable γ -ray bursts $0.01 - 100 \text{ s}$ $0.1 - 1 \text{ MeV}$
- Isotropic distribution (BATSE)
- X-ray afterglow (BeppoSAX) \Rightarrow optical and radio afterglows
- Beautiful exemple of multi-wavelength approach (same messenger!)
 - \Rightarrow Sources at cosmological distances
 - \Rightarrow Enormous energy release $\sim 10^{53} \text{ erg}$ + beaming
- Strong support for **fireball model** (review Piran 00)
 - energy source: accretion on a newly formed compact object
 - relativistic plasma jet flow
 - electron acceleration by shocks
 - γ -rays from synchrotron radiation
 - afterglows when jet impacts on surrounding medium
 - still many open questions

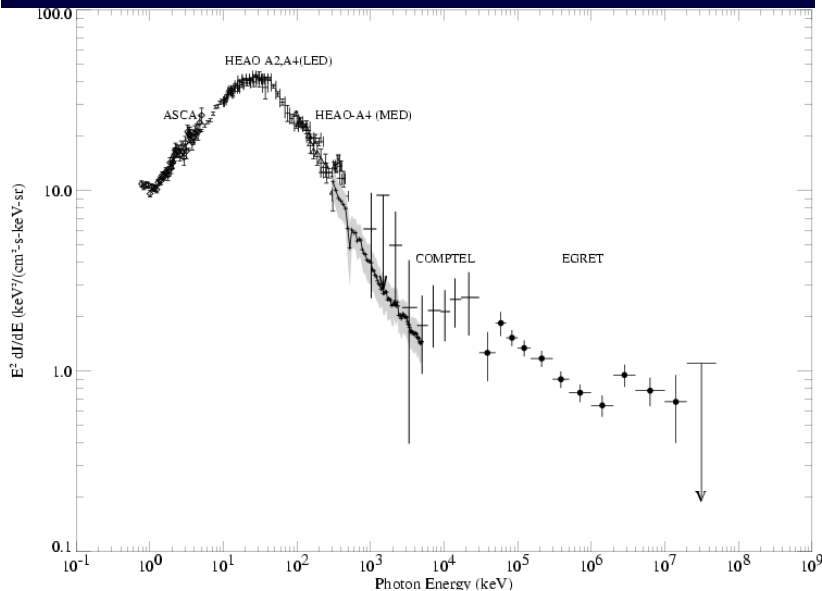
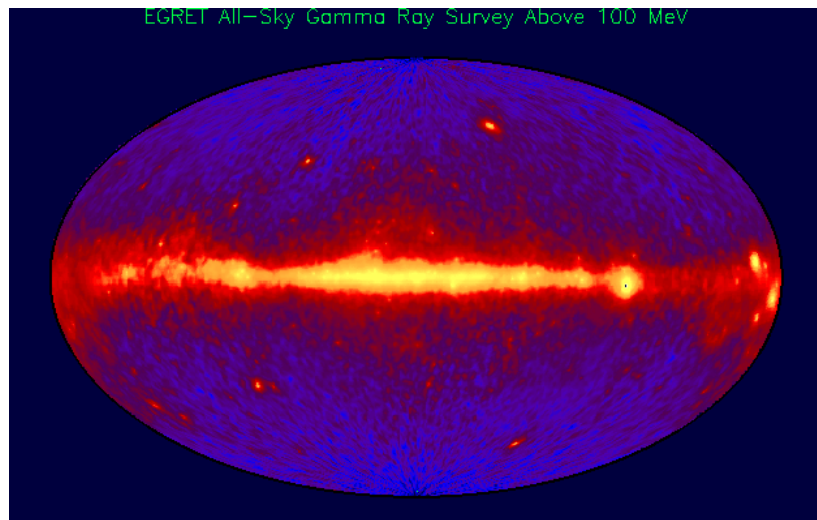


GRB : Connections

- **can UHE Cosmic Rays be explained by GRB's ?** Waxman 95, Pietri 95
Milgrom-Usov 95
 - relativistic plasma jet can also accelerate protons to $\sim 10^{20}$ eV
 - constraints on jet similar for p acceleration and γ emission (although indep.)
 - energy generation rates similar
- **HE neutrinos are expected**
 - accelerated p interact with fireball photons and produce pions
 - ν_μ from charged $\pi \Rightarrow \nu_\mu, \nu_\tau$ on Earth $\sim E_\nu^{-2}$
 - expect 20 evts/yr in a 1 km³ detector up to 10^{16} eV (Waxman-Bahcall 01)
 - correlated in time and direction with GRB
- **central engine also emits GW (compact object, relativistic motion)**
 - scenarios to get BH+accretion disk : NS-NS, NS-BH mergers, failed SN
 - 'canonical' GW sources (inspiral \rightarrow merger, collapse)
 - LIGO-Virgo only sensitive to 30 Mpc, advanced LIGO-Virgo to 400 Mpc
 - BH ringdown has a distinct signature (normal modes, damped sine GW)

γ -ray signatures of Dark Matter (1)

Extragalactic γ -ray background and heavy DM



Space Telescopes: EGRET → GLAST
30 MeV – 10 GeV

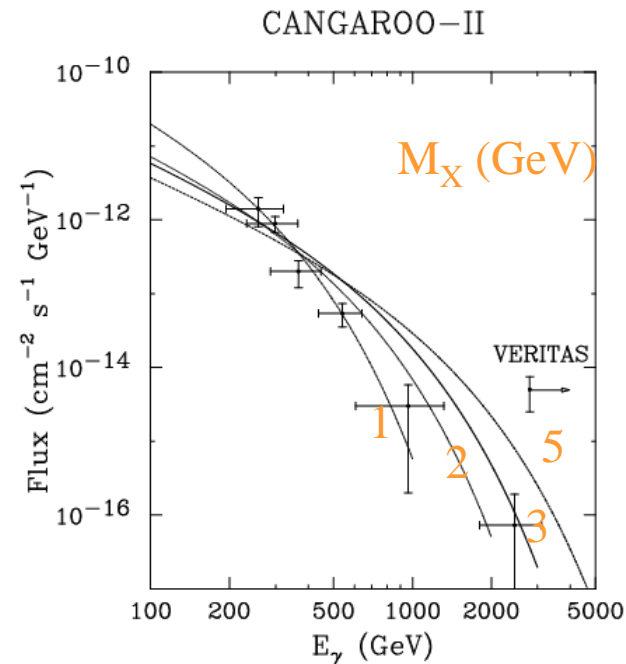
extragalactic component difficult to determine
(isotropy not enough, need model of Galactic background, not firmly established) Strong 04
superposition of all unresolved sources (AGN)

? could the HE component result from self-annihilating DM particles (such as SUSY LSP)
Elsässer-Mannheim 04 : possibly substantial contribution if mass = 0.5 – 1 TeV, very sensitive to the DM distribution in the Universe

more conventional models work (Strong 04a)

γ -ray signatures of Dark Matter (2)

TeV photons from the Galactic center and heavy DM



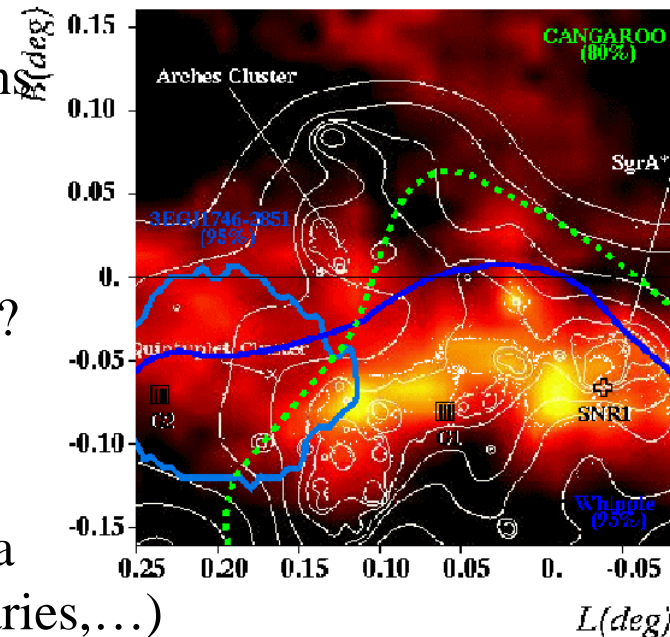
Atmospheric Cerenkov Telescopes: 200 GeV – 10 TeV
Whipple, CAT, HEGRA, VERITAS, CANGAROO II, HESS, MAGIC...

Spectrum from Galactic center: inconsistency between CANGAROO and VERITAS (quid est veritas?)

Center ($10^6 M_\odot$ BH) or nearby sources ?

complex region

complementary informations
from X-rays and radio



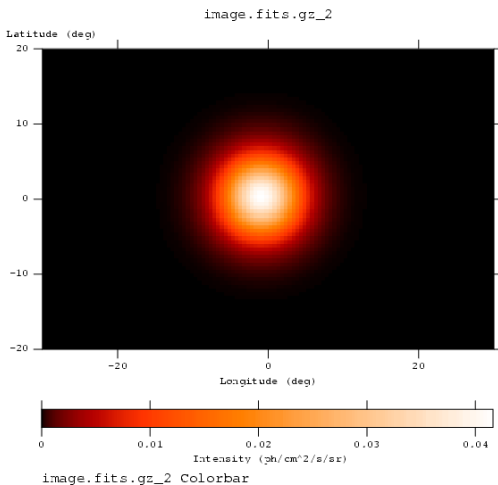
Hooper 04: self-annihilating heavy DM

$X X \rightarrow \text{hadrons}, \pi^0 \rightarrow \gamma\gamma$ lines from $X X \rightarrow \gamma\gamma, \gamma Z$?

- ?
- need large cross sections and high densities
 - very cuspy halo or spike at Galactic center
 - M_X : 1 TeV or 5 TeV ? waiting for HESS data
 - different interpretations (SN remnants, X-ray binaries,...)

γ -ray signatures of Dark Matter (3)

511 keV line from the Galactic bulge and light DM



Clear observation by **SPI/INTEGRAL** of a signal from e^+e^- annihilation at rest in an angular range compatible with the galactic bulge, inconsistent with a single point source

What is the source of positrons ?

‘standard’ explanation: SN Ia with β^+ radioactivity of produced nuclei, but rate appears to be too small (**Schanne 04**)

Cassé 04, Fayet 04 : **light DM particles**

ϕ spin $\frac{1}{2}$ or 0 $m_\phi \sim O(1 \text{ MeV})$

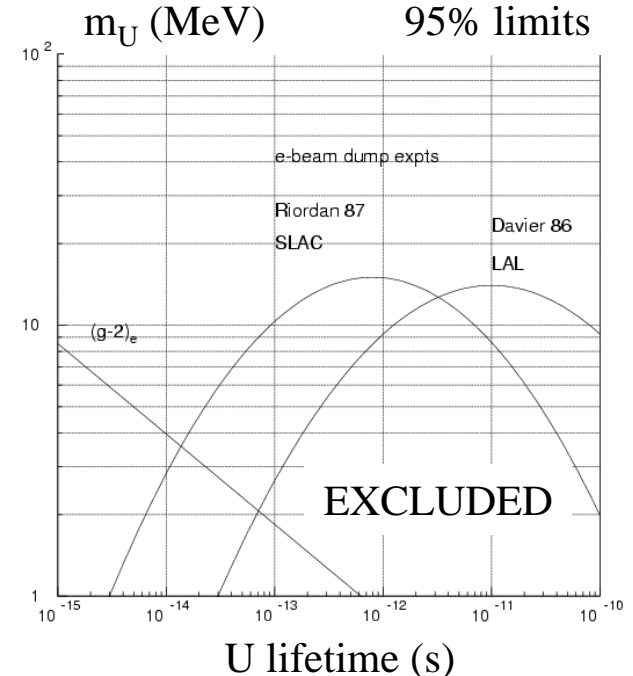
coupled to a light vector boson U

$m_U \sim 1 - 100 \text{ MeV}$ (lower range favoured)

$\phi \phi \rightarrow U \rightarrow e^+ e^-$

astrophysical tests proposed

severely constrained by particle physics



Gravity Wave Detectors

GW : quadrupolar deformation of space-time metrics

amplitude $h = \Delta L / L \Rightarrow$ interferometric detection well suited

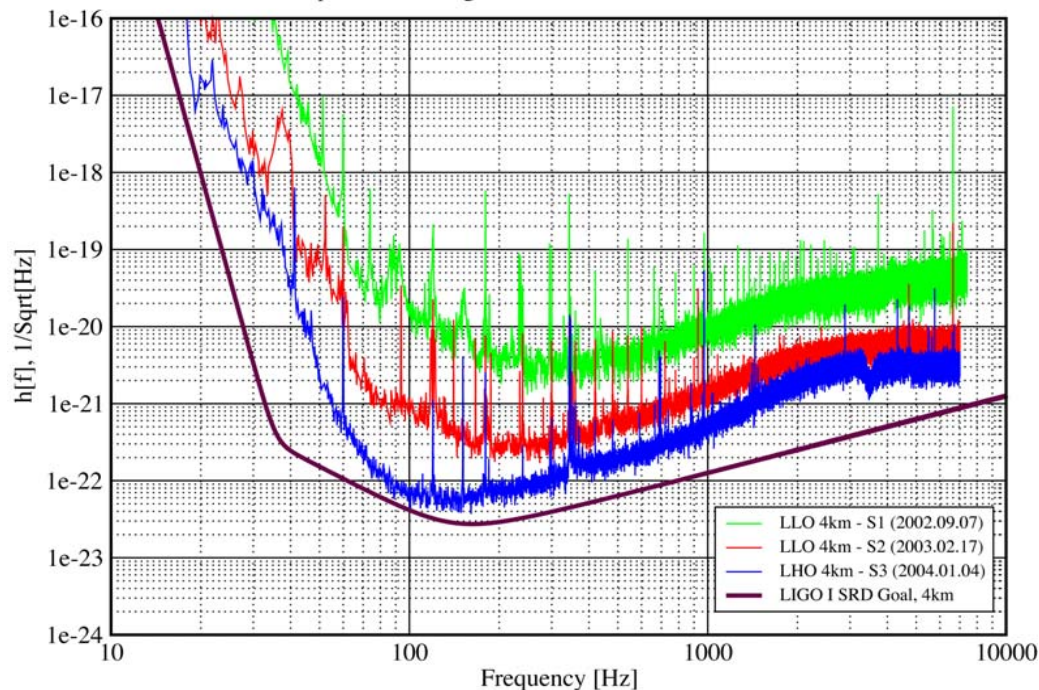
Large interferometric antennas coming into operation:

TAMA (Japan), LIGO-Hanford/Livingston (US),

GEO (Germany-UK), Virgo (France-Italy)

Best Strain Sensitivities for the LIGO Interferometers

Comparisons among S1, S2, S3 LIGO-G030548-01-E



LIGO close to nominal sensitivity

Science runs started

S1 (Sept 2002)

S2 (Feb 2003)

S3 (Jan 2004)

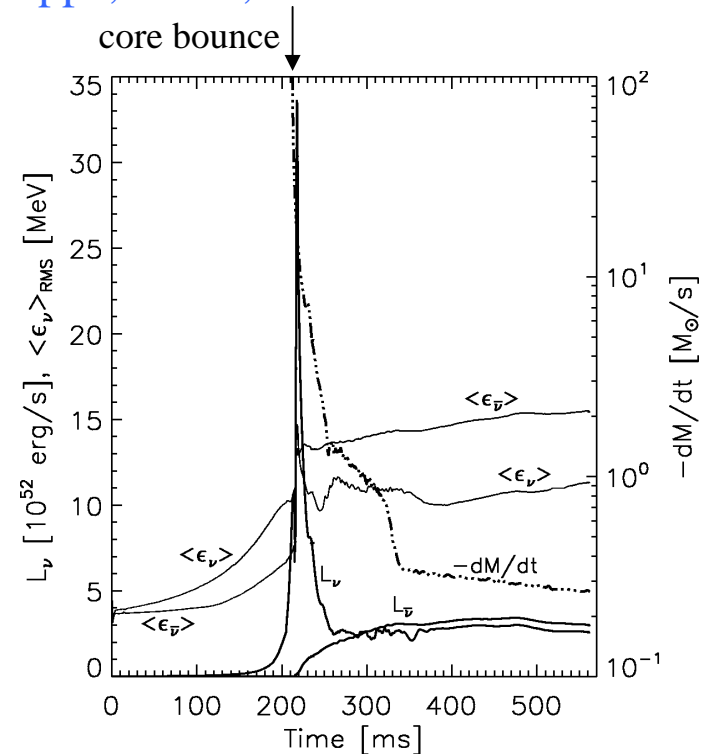
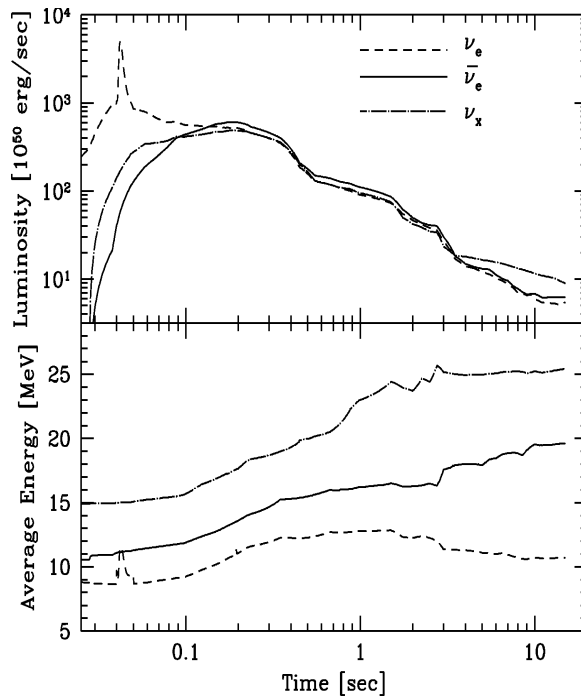
Virgo completed and being
commissioned
data taking in 2005

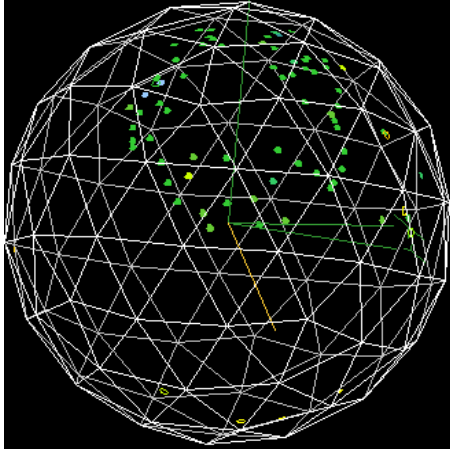
Chronology of stellar collapse

- Core collapse $p \ e^- \rightarrow n \ \nu_e$ **neutronization**
- supernuclear densities: 'ν sphere inside core (ν trapped)
- Shock wave bounce propagating from deep inside core
⇒ **GW burst** within a few ms
within < 1 ms shock wave passes through ν sphere
⇒ **initial ν_e burst (flash)** a few ms
- High T $e^+ \ e^- \rightarrow \nu_i \ \bar{\nu}_i$ all ν types (e , μ , τ)
shock turns on release of ν_e and ν_i ν_i pairs
⇒ **main ν burst** **1-10 s long**
- Accretion and explosion (ν heating of shocked envelope)
⇒ **optical signal** delayed by a few hrs

Simulation of neutrino burst

- Model-independent properties
 - 99% of initial binding energy into ν 's (1–2 % in early flash)
 - about $3 \cdot 10^{53}$ erg released $\langle E_\nu \rangle = 10 - 20$ MeV
- Detailed numerical simulations
 Mayle, Wilson, Barrows, Mezzacappa, Janka,



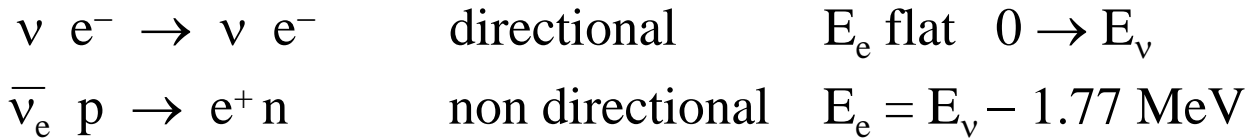


Neutrino detection

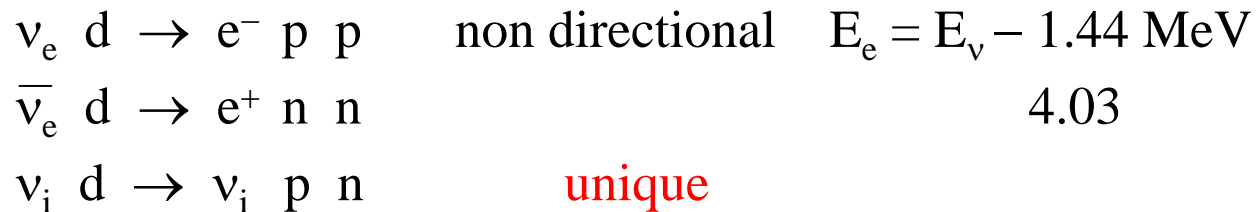
best operating detectors are water Cerenkov :

SuperK (32 kt) SNO(1 kt heavy water)

- **SuperK** e^\pm detection



- **SNO** e^\pm and neutron (delayed) detection



Neutrino event rate (SN at 10 kpc)

	SuperK	SNO	LVD
ν_e	91	132	3
$\bar{\nu}_e$	4300	442	135
ν_μ, ν_τ	(40)	207	(7)
ν_e flash	12	9	0.4
all	4430	781	146

Supernova GW detection

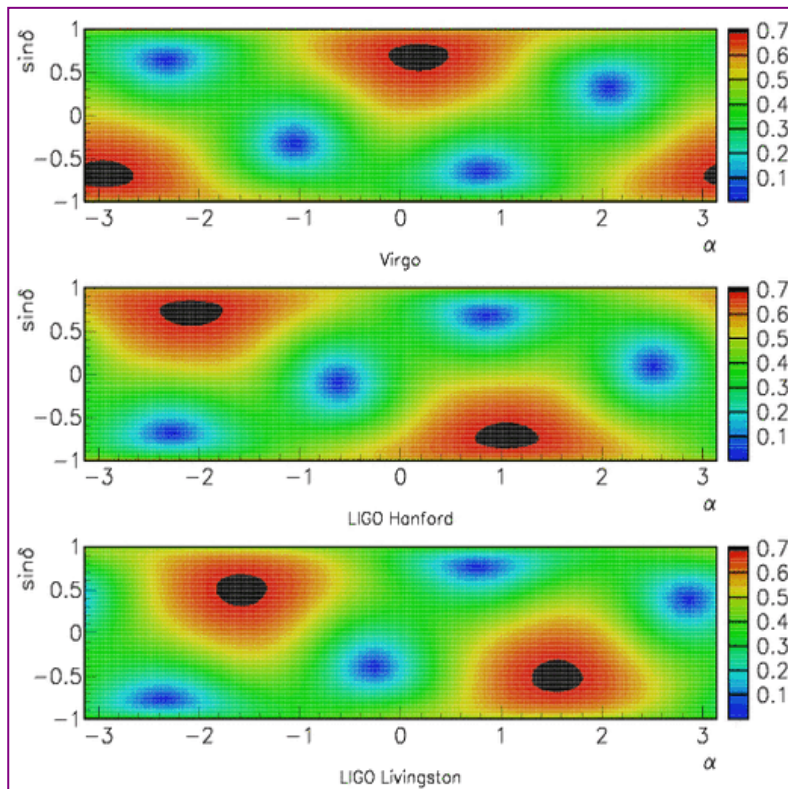
(1) Expected amplitude (simulations Zwerger-Müller 97)

LIGO-Virgo

$d_{\text{mean}} \sim 30 \text{ kpc}$ threshold $\text{SNR} = 5$

\Rightarrow detection limited to our Galaxy

(2) Antenna patterns

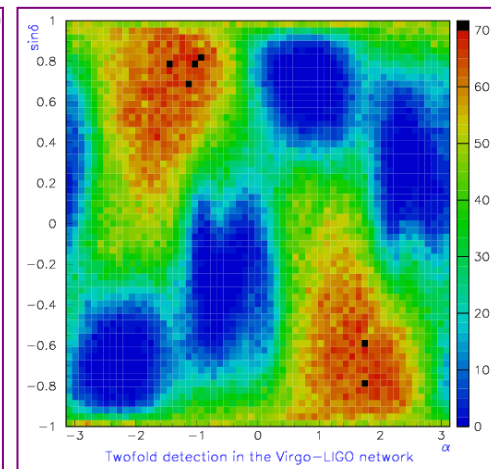
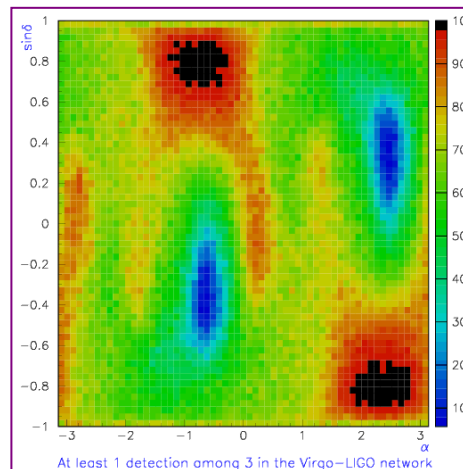


- Sky maps averaged over GW source polarization angle
- 2 LIGO interferometers mostly parallel
- Virgo nearly orthogonal to LIGO

Virgo-LIGO

1/3

2/3



The next Galactic SN : GW- ν coincidence strategy (1)

Arnaud 03

- **ν detectors**

- several running detectors covering the Galaxy with an efficiency of 100%
- false alarm rate negligible if at least 2 in coincidence
- direction to $\approx 5^\circ$ (best precision from delayed optical observation)
- SNEWS network : alarm to astronomers + GW detectors within 30'

- **GW interferometers**

- relatively low threshold barely covers Galaxy, but false rate too high
(assuming gaussian stationary noise, not realistic, so even worse)
- not suitable for sending alarms
- very important to react on ν alarms (discovery of GW from SN collapse)
- at least 2 antennas with complementary beam patterns needed for sky coverage, at least 3 to perform coincidences at reasonable efficiency

GW- ν coincidence strategy (2)

loose coincidence strategy: correlate GW signals in **several** antennas without directional information (time window ± 50 ms, maximum time delay between antennas)

tight coincidence strategy: knowing source direction (from ν or optical), time window can be reduced to ≈ 10 ms

coherent analysis : knowing source direction, outputs of all interferometers can be summed with weights \propto beam pattern functions, only **one threshold** on sum, **tight coincidence** applied with neutrinos

Two goals:

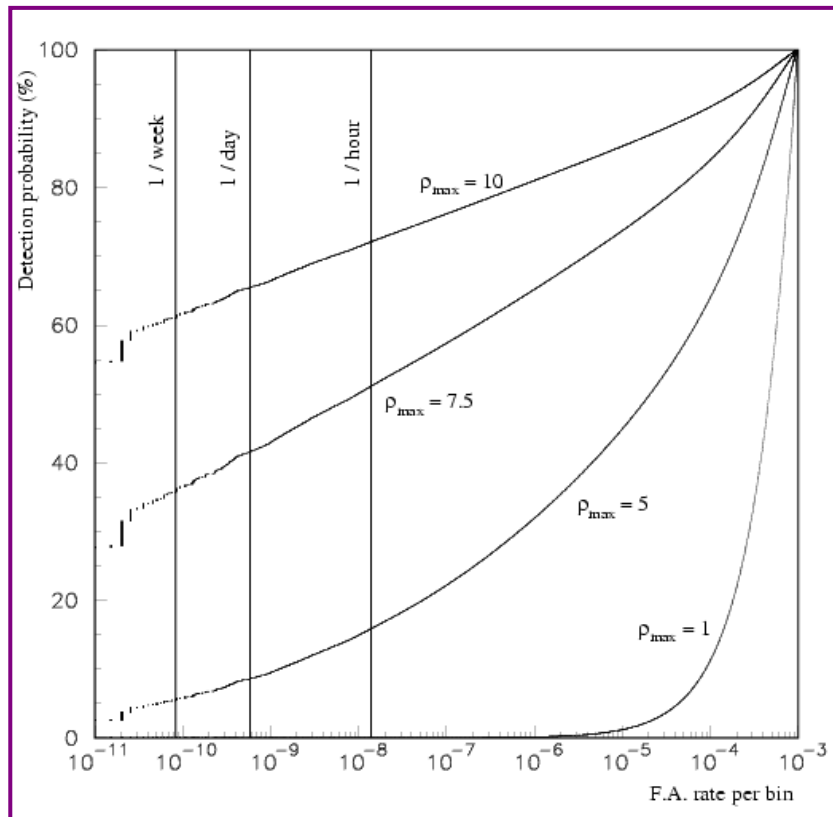
- claim the **discovery** of GW emission in the SN collapse : require 10^{-4} **accidental coincidence probability** in 10 ms window
- **study** GW signal in coincidence with neutrinos : 10^{-2} enough

GW- ν coincidence strategy (3)

LIGO – Virgo network

Arnaud 03

Detection Probability in Coherent Analysis



False Alarm rate in sampling bin (20 kHz)

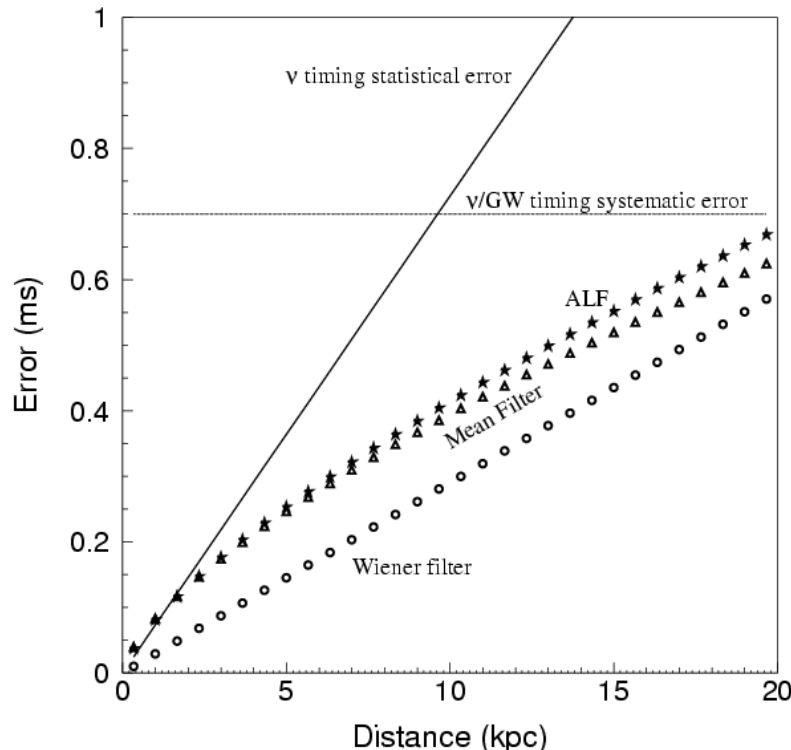
Accidental coincidence in 10 ms

Efficiency (%)	10^{-4}	10^{-2}
Coincidence 2/3	55	66
OR 1/3	71	85
Coherent	80	91

⇒ Coherent analysis provides best efficiency for SN GW confirmation

GW/neutrino timing

- **SYST**: GW peak time / bounce (0.1 ± 0.4) ms Zweiger-Muller 97
- **SYST**: ν_e flash / bounce (3.5 ± 0.5) ms simulations
- **STAT**: GW peak time accuracy < 0.5 ms depends on filtering algorithm
- **STAT**: ν_e flash accuracy = $\sigma_{\text{flash}} / \sqrt{N_{\text{events}}}$ with $\sigma_{\text{flash}} = (2.3 \pm 0.3)$ ms



Arnaud 02, 03

to reduce systematic uncertainty
joint simulations needed

GW/neutrino delay

Pakvasa 72, Fargion 81, Arnaud 02

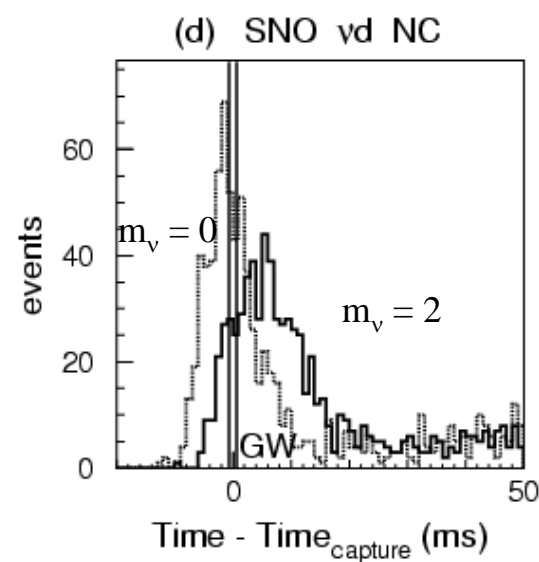
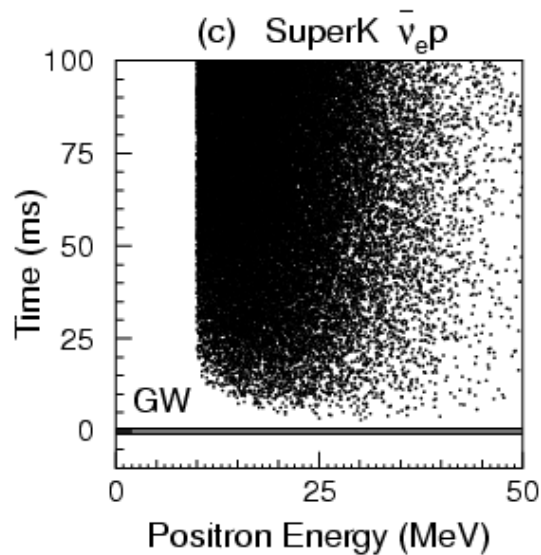
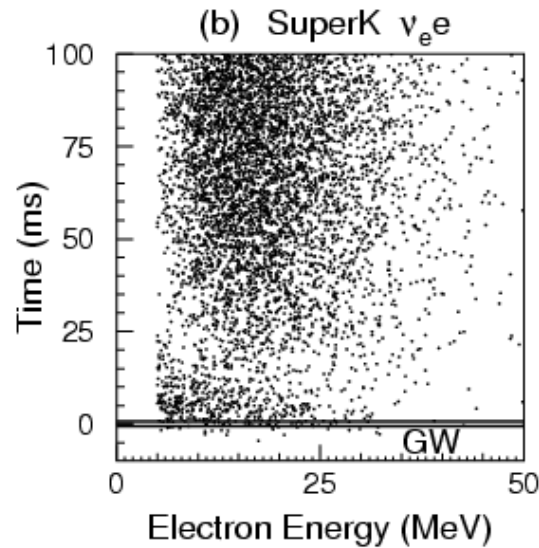
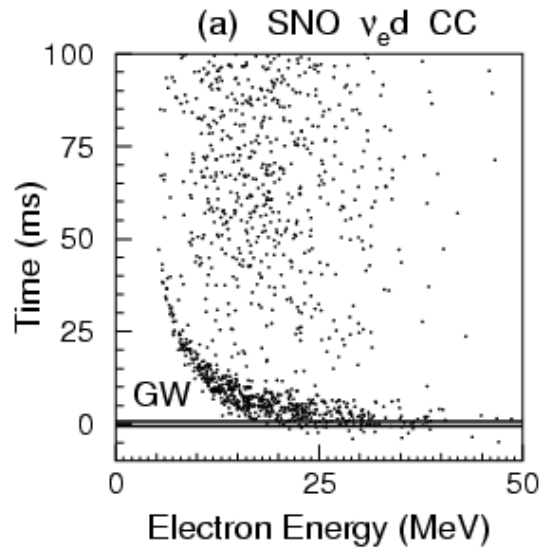
timing between the GW peak and the ν_e flash

$$\Delta t_{\nu, \text{GW}} = \Delta t_{\text{prop}} + \Delta t_{\nu, \text{bounce}} + \Delta t_{\text{GW, bounce}}$$

$$\begin{aligned} \Delta t_{\text{prop}} &= (L / 2) (m_\nu / E_\nu)^2 \\ &= 5.2 \text{ ms } (L / 10 \text{ kpc}) (m_\nu / 1 \text{ eV})^2 (10 \text{ MeV} / E_\nu)^2 \end{aligned}$$

- yields $\delta m_\nu^2 \propto \Delta t / L \approx \text{constant}$
- accuracy of $\approx 1 \text{ ms}$ gives sensitivity to neutrino masses $< 1 \text{ eV}$
- direct and absolute measurement
- if ν_e mass obtained from other exp. to a precision $< 0.5 \text{ eV}$, then GW/ ν_e timing provides unique information on bounce dynamics

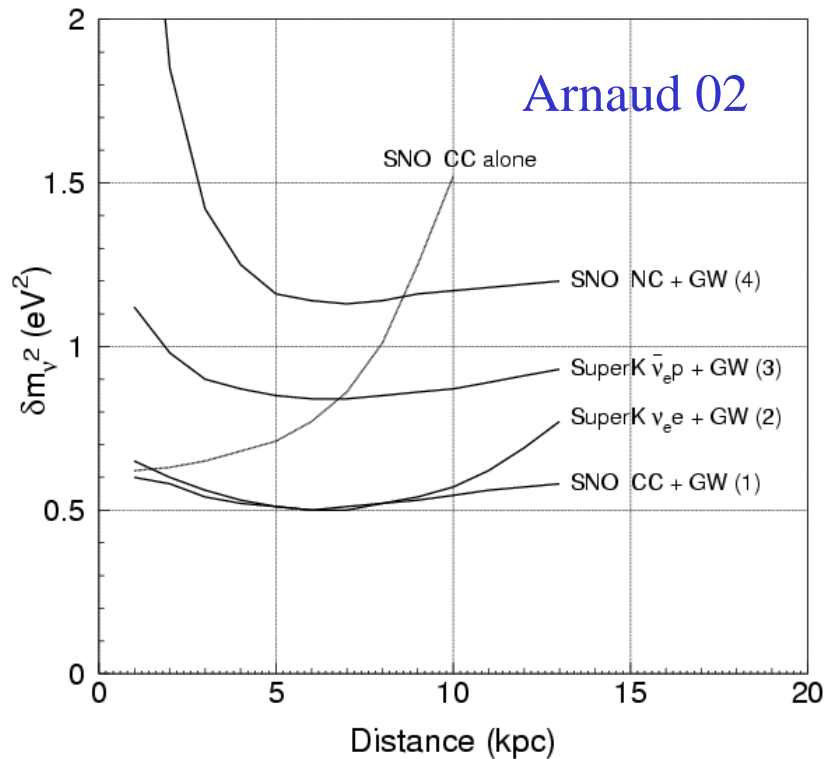
Simulating the experiment



SN collapse at 10 kpc
statistics x100
 $m_\nu = 2$ eV

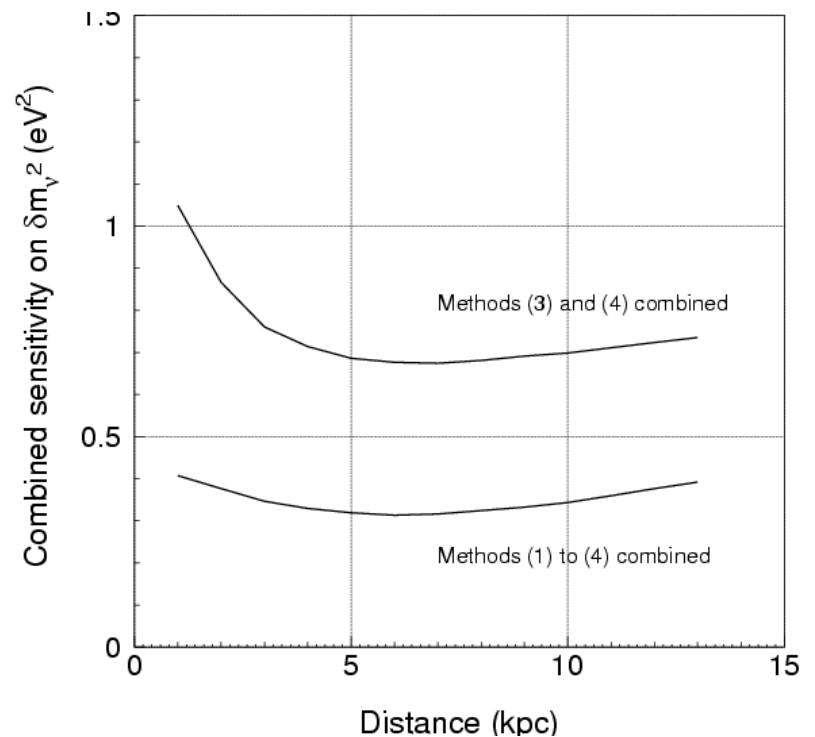
Arnaud 02

Expected results



- methods (1,2) with $P_e = 0.5$
- method (4) when $P_e = 0$
- method (3) whatever P_e

- results take into account neutrino oscillations (Dighe 00)
- relevant parameter: ν_e survival probability P_e (θ_{13})



Supernova physics (1)

neutrino detection : time and energy spectra for ν_e and $\bar{\nu}_e$
 time spectrum for $\nu_{\mu,\tau}$
 luminosity (distance)

GW detection : timing (bounce)
 amplitude

timing of neutrino pulses / bounce to better than 1 ms
if ν mass known or < 0.5 eV

learn about size of neutrinosphere (core opacity) and shock wave
propagation velocity

Supernova physics (2)

an interesting possibility : inner core collapse + accretion from outer mantle
 \Rightarrow delayed Black Hole formation ≈ 0.5 s

abrupt cutoff in neutrino time spectrum ≈ 0.5 ms

could be used as a timing signal

to observe late neutrinos, but mass sensitivity limited to 1.8 eV
(Beacom 2000)

to search for BH ringdown signal in GW antennas : could run
with relatively low threshold thanks to excellent timing,
matched filtering (damped sines)

observations of a sharp cutoff in the neutrino time spectrum
and a synchronized GW ringdown signal would constitute
a smoking gun evidence for BH

Conclusions (1)

- Complementary information on astrophysical phenomena is vital
- So far only used extensively with EM signals from radio to γ -rays (ex. GRBs)
- SN 1987a : extra-solar ν signal for the first time
- Study of the most violent events (collapses, mergers) will benefit enormously from the availability of γ , UHE cosmic rays, ν and GW detectors available and under construction
- Multiwavelength approach to cover a broad range of phenomena:
 - EM to-day's astrophysics
 - ν from 5 MeV to 1000 TeV
 - GW Ligo-Virgo 10 Hz – 10 kHz LISA 0.1 – 100 mHz
- Rates are small : need for large instruments
- Important to narrow the range of astrophysical interpretations

Conclusions (2)

- A single Galactic SN event seen in coincidence in GW and ν detectors would bring unique information.
- Sky coverage requires OR-ing several antennas with complementary beam patterns.
- LIGO-Virgo network will be 80% efficient to discover GW emission by a SN seen by ν detectors with an accidental coincidence probability of 10^{-4} .
- Precise GW/ ν timing can be achieved at better than 1 ms.
- Absolute neutrino masses can be investigated below the present lower limit of 2 eV down to 0.6 – 0.8 eV in a direct way.
- When ν masses are known from other methods or found to be smaller than 0.5 eV, relative GW/ ν timing provides a new tool to investigate SN physics.
- If the SN eventually collapses into a BH, a GW/ ν coincidence analysis can prove the BH formation.